A review of physical supply and EROI of fossil fuels in China

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Abstract: This paper reviews the future fossil fuel supply from the perspectives of physical supply and net energy output. Comprehensive analyses of physical supply of fossil fuels show that China's total oil production will peak at 228.4 Mt in 2018, its total gas production will peak at 370 bcm in 2040, while the coal production will peak at 4404 Mt in 2021. The significant differences among current studies can be mainly explained by different URR assumptions, applied models and historical production data. The great gap between domestic supply and demand will appear due to constrained production of fossil fuels and need to be met by imports. Net energy analyses show that both coal and oil & gas show a steady declining trend of EROI due to the depletion of shallow-buried coal resources and conventional oil & gas resources. The declining trend of EROI is generally consistent with the approaching of peak physical production of fossil fuels, which, coupled by the declining EROI, may challenge the sustainable development of the Chinese society unless new abundant energy resources with higher EROI value can be found.

Keywords: Peak production; Fossil fuels; Net energy; EROI, China

1 Introduction

China has achieved a rapid economic growth since its beginning of reform and opening up, with an average annual growth rate of 9.8% of GDP from 1978-2014 (NBSC, 2015). Currently, China has become the second-largest economy in the world after the United States. This great achievement can't be done without large amounts of energy consumption. From 1978 to 2014, China's total energy consumption has increased from 571.44 million tons of coal equivalent (Mtce) to 4260 Mtce, with an average annual growth rate of 5.8% (NBSC, 2015). Moreover, most of these energies are from fossil fuels. In 2014, total fossil fuel consumption is 3782.88 Mtce (coal: 2811.60Mtce; oil: 728.46Mtce; gas: 242.82Mtce), accounting for 88.9% of total energy consumption (NBSC, 2015). In the future, a number of studies have pointed out that fossil fuels will still dominate China's energy consumption and their demand will keep increasing in future although increase rate may be lower (Yuan et al., 2016; IEA, 2014). In this case, it's very important for China to understand its supply status of fossil fuel resources.

Guo and Li (1997) published the first peer-reviewed article to discuss the supply status of China's conventional oil resources. Thereafter, a number of studies appeared to quantitatively analyze the fossil fuel supply of China (Tao and Li, 2007a, 2007b; Feng et al., 2007, 2008a, 2008b). The results in different studies may differ sharply. For example, Mohr and Evans (2009) forecasted that the peak production of China's coal resources is about 2300 million tons (Mt), while the peak production is forecast to be more than 6000 Mt in the study of Li (2010). Due to its significant difference, policies relying only one result may have considerable risk. Therefore, it's crucial to present a comprehensive review of these previous studies and convince a full idea about the future supply of China's fossil fuels to policy makers.

The main aim of this paper is to provide an idea of the supply status of China's fossil fuels by reviewing current available literature. Furthermore, the supply status of fossil fuel resources could be measured from two perspectives: one is physical perspective (i.e. physical supply or physical output), the other is net energy perspective (i.e. net energy output). Most of current studies are from the physical perspective. In 2011, Hu et al. (2011a) first introduced the concepts of net energy and EROI into China. Several studies appeared after 2011 to discuss the net energy or EROI for China's fossil fuel resources (Hu et al., 2011b, 2013, 2014a; Xu et al., 2014). To fully reflect the supply status of fossil fuel resources, the studies from net energy perspective are also reviewed in this paper.

2 Oil production

China became a net oil importer in 1993 and a net crude oil importer in 1996 (BP, 2015). Thereafter, a concern of the potential shortage of domestic oil supply has raised, and since then, studies of China's future oil production appeared.

2.1 Conventional oil production

Figure 1 and Table 1 show the results of China's conventional oil production studies. We can see different studies present very different results. According to these studies, the conventional oil production could have already peaked at 2002 or will peak at 2028 in the future. The peak production could be lower than 140 Mt or higher than 220 Mt. Many reasons could be responsible for these significant differences, and three of them are believed to be the most important. The first is different value of ultimately recoverable resources (URR). URR is a key input factor for most of forecast models (Wang and Feng, 2016). From Table 1 we can see that the lowest URR is 8.2 Gigtons (Gt), while the highest is 24.6 Gt. Wang et al. (2015) use the Multi-Cycle Generalized Weng model forecast that Chinese oil production will peak at 2025, with a peak production of 195 Mt; while Wang et al. (2016a) use the same forecast model but present different results (peak year is 2014, and peak production is 167 Mt). The main reason is that URR is 19.3 Gt in Wang et al. (2015) and 12.8 Gt in Wang et al. (2016a). A lot of literature have shown that the URR reported by China's authorities (URR with its value higher than 20 Gt in Table 1 are all from different reports of authorities) overestimate the actual URR due to little consideration on economic conditions (Wang et al., 2013). In addition, parts of unconventional resources are also included in statistic of conventional oil resources (Wang et al., 2013; Wang et al., 2016a).

The second reason is the forecast model. Currently, most studies used different type of curve-fitting models. According to Wang and Feng (2016), the curve shape has the considerable impacts on forecast results and can be either symmetric or asymmetric. Asymmetric curves can be further divided into negatively skewed and positively skewed shapes. Generally, the model with positively skewed curve shape will result in lower peak production and lower post-peak decline rate, while the model with negatively skewed curve shape will result in higher peak production and higher post-peak decline rate (Wang and Feng, 2016). Brandt (2007) analyzed 67 post-peak regions and found that the actual production curve in most regions is positive skew. Wang et al. (2011) also pointed out the positively skewed curve is better that symmetric curve in production forecasting. In Table 1, both HCZ and Generalized Weng models are positively skewed curve models. If we only consider the results of these models, some high forecast results may be excluded. The detailed discussion on the impacts of curve-fitting models on forecast results can be found in Wang and Feng (2016).

The third reason is the historical production data. From Table 1, we can see that most forecast models are curve-fitting models, which means the short-term trend of forecast curve will be affected by historical production data. In China's oil industry, there's no separate statistics for unconventional oil production. Therefore, the total historical oil production data is usually seen as the historical conventional oil production data by most researchers when they forecast Chinese conventional oil production. That's why many conventional oil forecast curves fit the total historical oil production data well in Figure 1. The study of Wang et al. (2015) is the first study that shows the conventional oil production and unconventional oil production separately by collecting the unconventional oil production data from various sources (See Figure 1). It can be seen from Table 1 that conventional oil production growth rate becomes significant lower if unconventional oil production is excluded from the total oil production.

In this paper, the average result of all collected data is used as our suggested result (see the average conventional oil curve in Figure 1). According to our suggest result, China's conventional oil production has entered its peak plateau since 2005, with a peak production about 160-170 Mt, then declined since 2014. It should be noted that our suggested result also considered those high forecast. Based on our above analyses, it may be expected that the actual production may be lower that our suggested result if lower URR, positively skewed curve model and the historical conventional oil production are used in modelling.

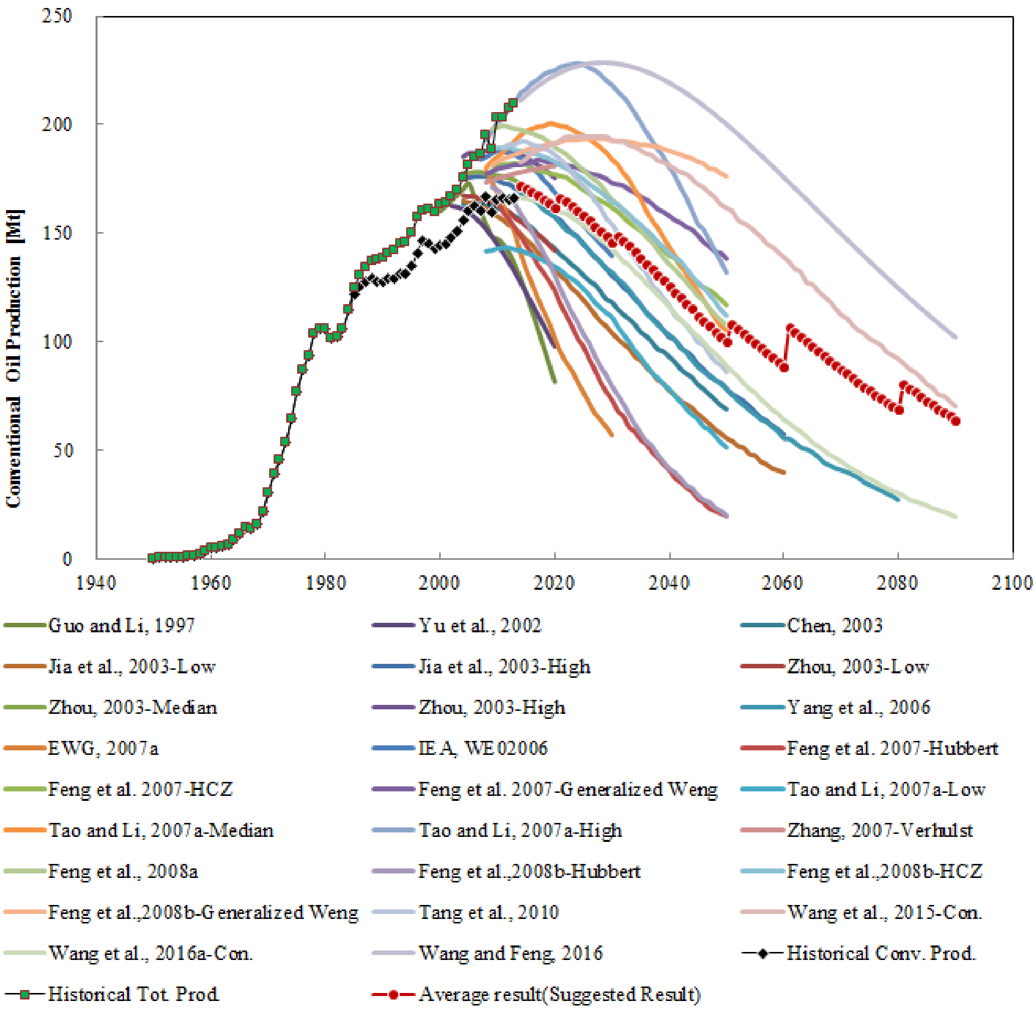

Figure 1. Production forecast for China's conventional oil resources

Table 1. Summaries of production forecast for China's conventional oil resources

Researchers	Methodology	URR [Gt]	Forecast results Peak Prod.[Mt]	Peak Year
Guo and Li, 1997	GM & Verhulst model	-	191	2005
Shen et al., 2000	-	14.0	200	2020
Wan, 2000	-	-	180	2020
Yu et al., 2002	Growth Curve model	-	163	2002
Chen, 2003	HCZ model	12.0	164	2005
Jia et al., 2003	-	11~14	180	2010
Zhou, 2003	Weng model	11~14	167~187	2004~2010
Mou, 2004	-	-	180~200	2020
Pang et al., 2005	-	-	175	2010
Yang et al., 2006	-	-	180	2007
Zhang and Jia, 2007	Analogy forecast model	-	190~236	2015~2037

EWG, 2007a	Logistic model	8.2	187	2006
Feng et al., 2007	Hubbert, HCZ, Gen. Weng		172~185	2005~2017
Tao and Li, 2007a	SD model	10~16	143~228	2010~2022
Feng et al., 2008a	HCZ model	15.6	198	2011
Feng et al., 2008b	Hubbert, HCZ, Gen. Weng	-	172~194	2005~2026
Pang et al., 2009	-	-	200	2026
Tang et al., 2010	SD model	13.4	193	2015
Wang et al., 2015	MCGW model	19.3	195	2025
Wang et al., 2016a	MCGW model	12.8	167	2014
Wang and Feng, 2016	Multi-Richards model	24.6	229	2028
Summary-Literature		8.2~24.6	143~229	2002~2028
Suggested result in this paper*			160~170	2005~2014

Note:

- is not available or qualitative analysis

GM-Grey Model

EWG-Energy Watch Group

SD model-System Dynamic model

MCGW-Multi-Cycle Generalized Weng

* is the average value of our collected data and our analysis

2.2 Unconventional oil supply

Figure 2 and Table 2 summarize the results of studies of China's unconventional oil resources. We can see there are only two studies focusing on unconventional oil. Wang et al. (2015) carried out the first quantitative study of China's long-term unconventional oil production by using two scenarios. The results under these two scenarios differ sharply. In the high scenario, the total unconventional oil production will grow considerably in future and reach its peak at 2068 with a peak production of 351.1 Mt, while in the low scenario, the total unconventional oil will reach its peak production of 48.7 Mt at 2023 (See Figure 1). The different URR assumption is the main reason for this significant difference. Just as claimed by Wang et al.(2015), there's no national systematic assessments for URR of each type of China's unconventional oil resources, therefore, URR assumptions in both two scenarios are not the actual URR value. Specifically, the technical recoverable resources (TRR) (which is 23.43 Gt) is used as the URR in the high scenario while "proved reserves plus cumulative production" (which is 2.2 Gt) is used as the URR in the low scenario. Based on these assumptions, Wang et al. (2015) claimed that the actual production will surely much lower than production shown in the high scenario but higher than one shown in the low scenario. Furthermore, Wang et al. (2015) claimed that their results are only consider the geological factors, if the economic factor and environmental factor are considered, the production should lower further.

Wang et al. (2016a) further developed the study of Wang et al. (2015) by including the economic factor in their analyses. Based on Wang et al.(2016a), the total unconventional oil production will peak at 2021, with a peak production of 65.5 Mt. The study of Wang et al.(2016a) shows that the actual production of unconventional oil resources is much lower than the results shown in the high scenario of Wang et al. (2015), and higher than the results shown in the low scenario of Wang et al. (2015).

In this paper, the results of Wang et al. (2016a) are used as our suggested results.

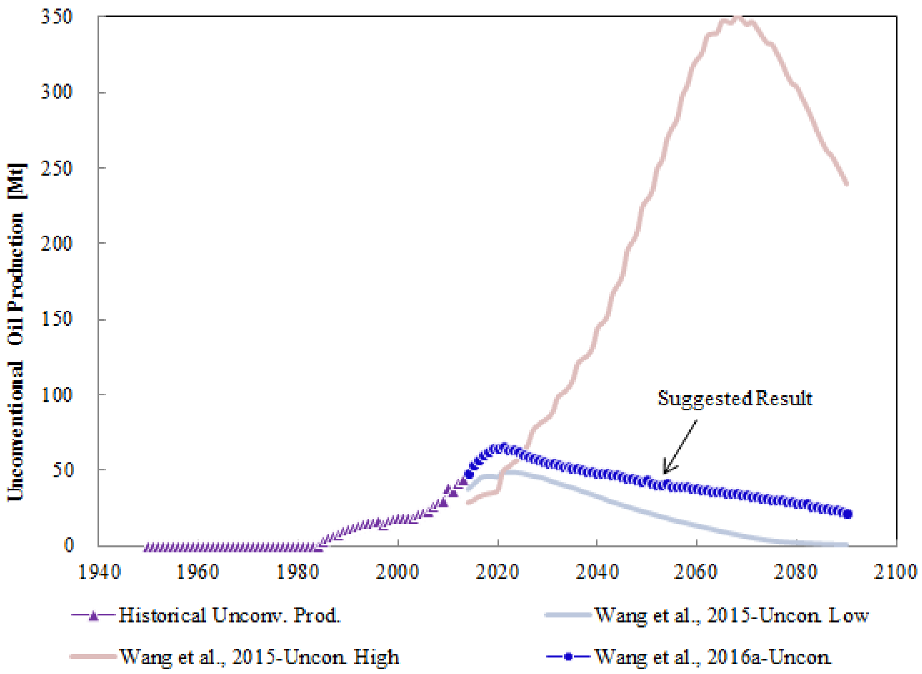

Figure 2. Production forecast for China's unconventional oil resources

Table 2. Summaries of production forecast for China's unconventional oil resources

Researchers	Methodology	URR	Forecast results	
		[Gt]	Peak Prod.[Mt]	Peak Year
Wang et al., 2015	GeRS-DeMo model	2.2~23.43	48.7~351.08	2023~2068
Wang et al., 2016a	SRCGM model	4.9	65.49	2021
Suggested result in this paper*		4.9	65.49	2021

Note:

GeRS-DeMo model-Geologic Resources Supply-Demand Model

SRCGM-Stochastic Resource-Constrained Growth Model

* is the value from Wang et al., 2016.

2.3 Total oil supply and its implications on China's oil use

Based on the above discussion on conventional oil and unconventional oil, we can get the total oil production in China (by combining the suggested results of conventional oil and unconventional oil). From Figure 3, we can see that China's total oil production will reach its peak at 2018, with a peak production of 228.4 Mt. By comparing total oil production in this paper and forecast total oil production in the New Policies Scenario of International Energy Agency (2014), we can see that IEA shows the similar oil production trend, although IEA's results are slight lower than our suggested results in this paper. Furthermore, Figure 3 also compares this paper's suggested oil production and IEA's forecast oil demand. It can be seen from the figure that China's future oil demand may peak around 2040, with a peak demand of about 780 Mt, and before that, the oil demand will keep its increasing trend. However, the total oil production data shown in this paper will be about 170 Mt in 2040, which means the oil shortage will increasing from 308 Mt in 2014 to 610 Mt in 2014, with an average annual growth rate of 2.7%. Based on this analysis, oil supply security will be still a serious concern for China. There's no other way to meet this shortage except oil imports. It's can be expected that international oil market will be affected by China's oil import trend significantly.

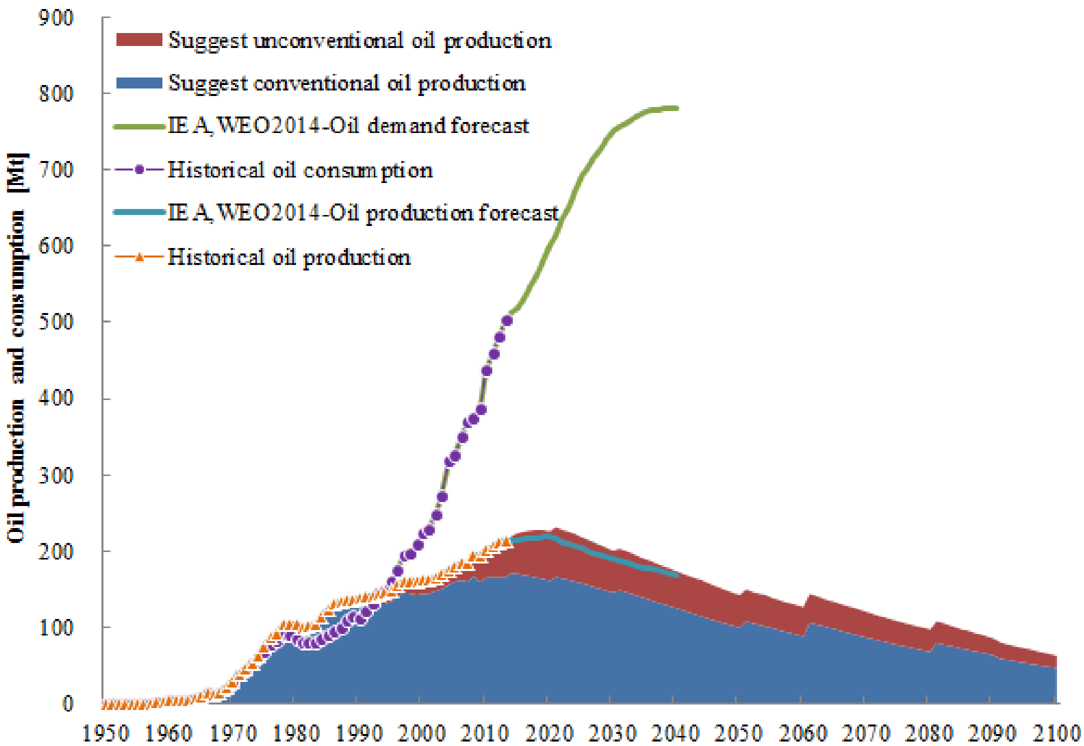

Figure 3. Comparison of China's domestic oil supply and forecast oil demand

3 Gas production

In the history of China's petroleum industry, the importance of oil is usually higher than gas because the gas consumption in China is much lower and increase very slowly due in part to lack of infrastructure. In 2004, the first West–East Gas Pipeline was finished, which has greatly promoted the growth of natural gas consumption. After that, China's gas consumption began to increase very rapidly, with an average annual growth rate of 16.4 % between 2004-2014 (BP, 2015). To meet this soaring gas demand, China's gas production also experiences a rapid growth during the same period, with an average annual growth rate of 12.2 % (BP, 2015). However, China's domestic production still can't fully meet its demand, and in 2007, China first become a net gas importer. Thereafter, many studies began to pay their attention to the long-term production potential of China's gas resources. Similar to the studies of oil production, most studies of gas production are for conventional gas resources, only one study focus on unconventional gas resources. Detailed analyses are shown in the following parts.

3.1 Conventional gas production

Figure 4 and Table 3 present the results of related studies of China's conventional gas production. Most of these studies appeared after 2007, which could be explained by the reasons shown in the previous paragraph. From the Figure 3, we can see the difference among these studies are significant. According to the studies, the peak year of China's conventional gas production will be 2019-2049, and the peak production will be 100-393 billion cubic meters (bcm). The reasons behind these difference are the same with conventional oil studies, i.e. URR assumptions, applied forecast models and the historical production data.

URR values from China's authorities are significantly higher than literature suggested. For example, according to the 3rd national oil and gas resource assessment, the URR of China's conventional gas resources is 22 Tcm (Li et al., 2006), this number has been used by several studies (see table 2). However, most literature show that the URR of China's conventional gas 6.7-13.3 Tcm, with an average value of 10.19 Tcm (Wang et al., 2013). Similar to conventional oil resources, URR estimate of conventional gas resources is also lack of fully consideration of economic factors. In addition, parts of tight gas resources are also included in conventional gas resources (Wang et al., 2013; Wang et al., 2016c).

The models used for gas production forecasting are the same with conventional oil production modelling and their impacts on results can be found in section 2.1.

For historical production data, similar to oil production data, there is no separate statistics for conventional gas from China's authorities(Wang et al.,2016c). Current studies usually use total gas production as the conventional gas production. Wang et al. (2016c) first present a comprehensive investigation of historical production data from various sources, and then, for the first time, we get the conventional gas production data by excluding the unconventional gas production from the total production data (see "Historical Conv. Prod." In Figure 4). During these reasons, we can see that most of forecast production curve fits the total production data well, rather than the conventional production data (see Figure 4).

In this paper, the average result of all our investigated studies is selected as our suggested result. From Figure 4 and the Table 3, our suggested result shows that China's conventional oil production will keep increasing in the next 14 years and reach its peak at around 2030, with a peak production of 196 bcm.

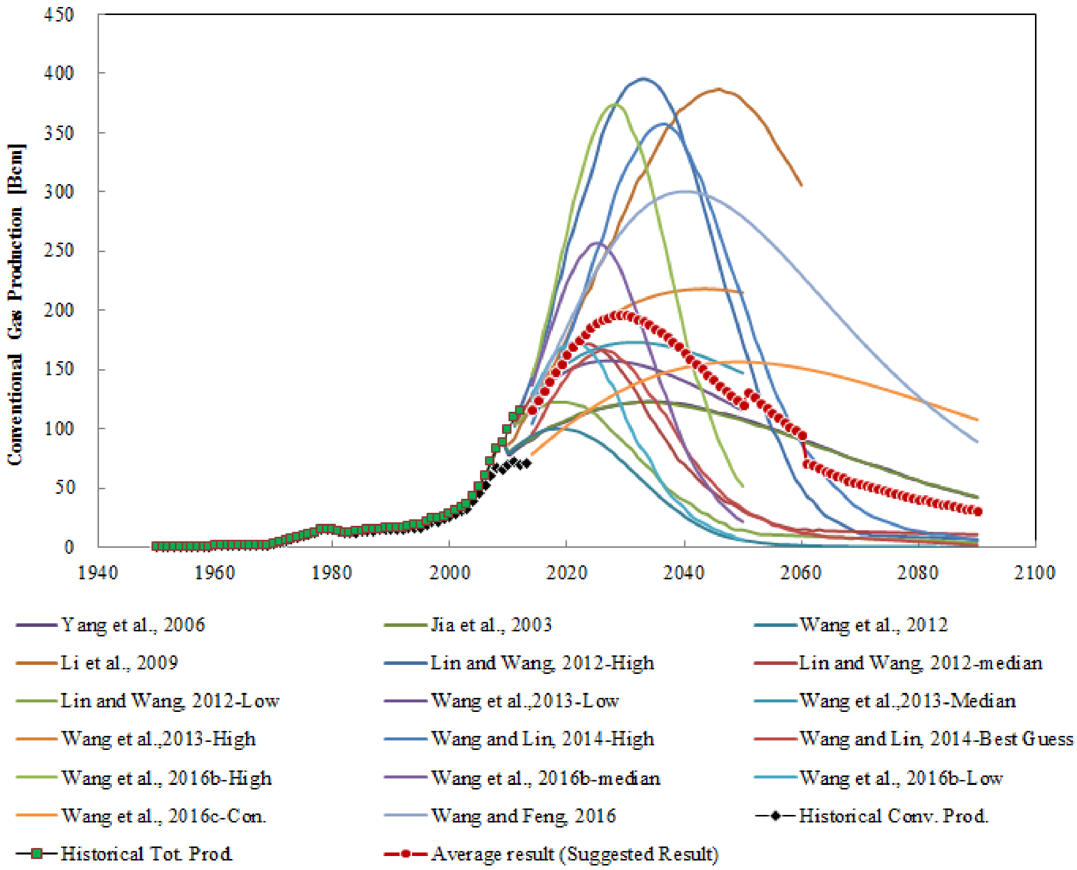

Figure 4. Production forecast for China's conventional gas resources

Table 3. Summaries of production forecast for China's conventional gas resources

Researchers	Methodology	URR[Tcm]	Forecast results	
			Peak Prod.[bcm]	Peak Year
Hu, 1999	Generalized Weng model		104~142	
Wan, 2000	-	-	100	2020
Jia et al., 2003	-	10~14.7	120	2035
Mou, 2004	-	-	150	2020
Pang et al., 2005	-	-	110	2026
Yang et al., 2006	-	-	125	2034
Pang et al., 2009	-		200	2026
Li et al., 2009	Combined model*	22	387	2046
Wang et al., 2012	Gaussian model	2.46	101	2018
Lin and Wang,2012	Gaussian model	3.82~12.82	117~393	2019~2033
Wang et al., 2013	MCGW model	10.19~22	157~218	2027~2043

Wang and Lin, 2014	Logistic model	5.28~12.82	165~356	2025~2035
Wang et al., 2016b	Multi-cycle Hubbert model	4.63~10.19	174~376	2019~2028
Wang et al., 2016c	MCGW model	16.75	156	2049
Wang and Feng, 2016	Multi-cycle Richards model	22	300	2040
Summary-Literature		2.46~22	100~393	2019~2049
Suggested result in this paper**		11.41	196	2030

Note:

- is not available or qualitative analysis

MCGW-Multi-Cycle Generalized Weng

* is the model that combines Hubbert, HCZ and Generalized Weng model

** is the average value of all collected data

3.2 Unconventional gas production

As stated in the previous section, Wang et al. (2016c) is the only study that makes a comprehensive investigation of historical production data and resources/reserves data for each type of unconventional gas resources. Based on these investigated data, Wang et al. (2016c) carried out the first quantitative study of China's long-term unconventional gas production by using Geologic Resources Supply-Demand Model (GeRS-DeMo), which is a widely used model for developing the projections of unconventional fossil fuel production (Mohr and Evans, 2010, 2011; Wang et al., 2015). In Wang et al. (2016c), three scenarios based on different URR assumptions are developed, i.e. the high scenario (TRR is treated as URR in this scenario), the low scenario ("Proved reserves plus cumulative production" is used as URR in this scenario), and the median scenario (the average value of high and low scenarios is used as URR in this scenario). It should be noted that geological factor is the only factor considered in the modelling process. Therefore, the forecast results of Wang et al. (2016c) should be seen as the upper bound of the future production, and the actual production would be surely lower than results shown in Wang et al. (2016c).

In this paper, the median result of Wang et al. (2016c) is used as our suggested result. Based on this result, we can see that China's unconventional gas production will increase significantly in the future and peak at 2058, with a peak production of 266 bcm.

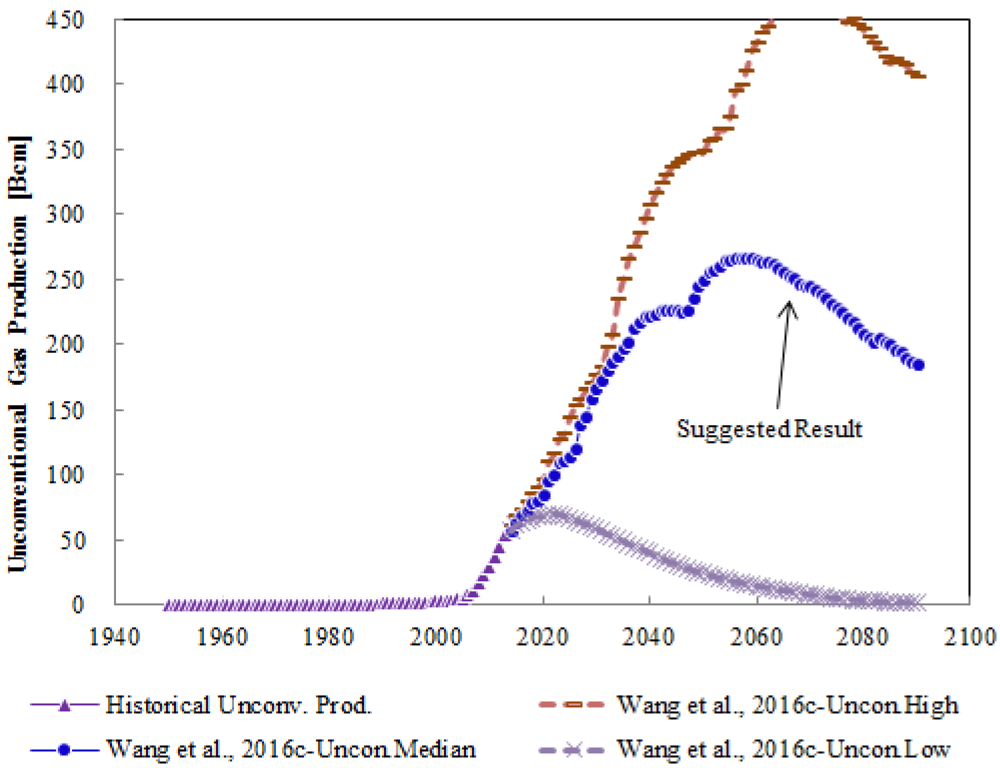

Figure 5. Production forecast for China's conventional gas resources

Table 4. Summaries of production forecast for China's unconventional gas resources

Researchers	Methodology	URR[Tcm]	Forecast results	
			Peak Prod.[bcm]	Peak Year
Wang et al., 2016c	GeRS-DeMo model	2.49~42.44	70~470	2021~2069
Suggested result in this paper*		22.46	266	2058

Note:

MCGW-Multi-Cycle Generalized Weng

GeRS-DeMo model-Geologic Resources Supply-Demand Model

* is the value for the median case of Wang et al., 2016c

3.3 Total gas production and its implications on China's gas use

China's total gas production are forecast to keep increasing and reach its peak at 2040, with a peak production of 370 bcm, then decline, according to our suggested results. Unconventional gas will play a key role in future total gas production growth, and its contribution will surpass conventional gas in 2036. IEA (2014) also forecast the total gas production in the period of 2012-2040. According to IEA (2014), China's total gas production will keep increasing before 2040, which is similar with our suggested results. However, IEA's forecast shows no indication of production peaking at 2040. A comparison of the total gas production suggested in this paper and the forecast gas demand in the New Policies Scenario of IEA (2014) is also presented in Figure 6. It can be seen from Figure 6 that China's gas demand will increase very rapidly in the next several decades. In 2040, the gas demand will be 600 bcm approximately, while China's total gas production will only be 370 bcm, even considering the rapid production increase in its unconventional gas recourses. The gap between domestic production and demand will reach 230 bcm in 2040 and is forecast to increase rapidly after 2040 since the production will decline after 2040.

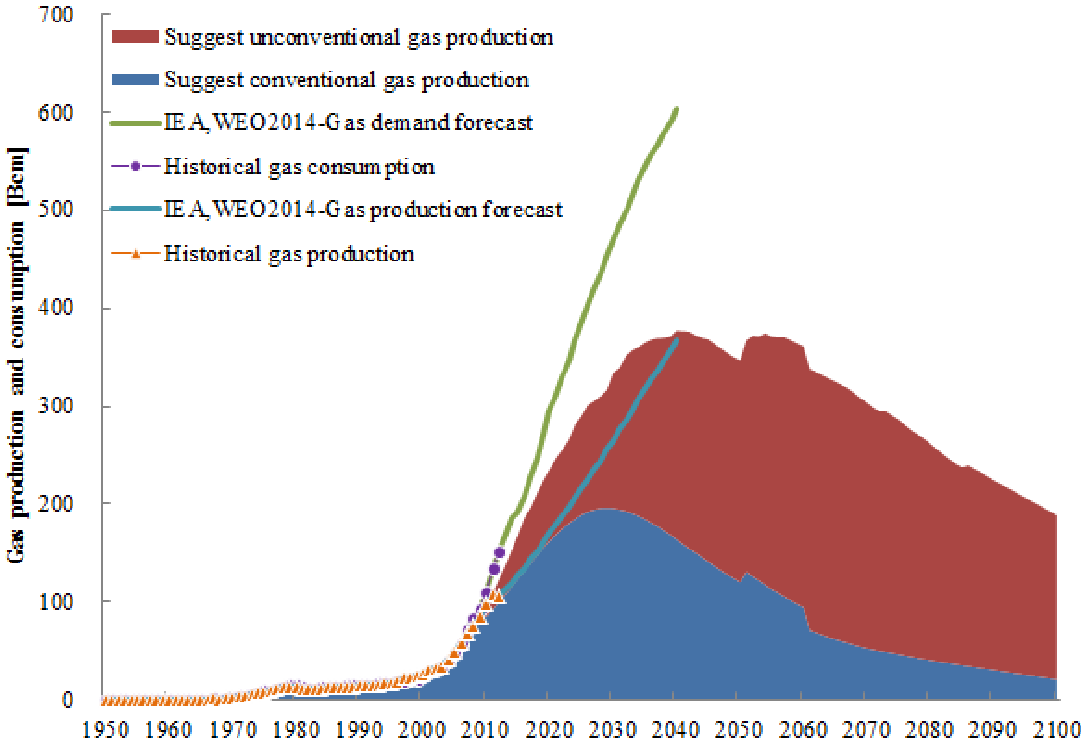

Figure 6. Comparison of China's domestic gas supply and forecast gas demand

4 Coal production

Coal holds the domain position in China's energy industry. In 2014, 73.2 % of total energy supply and 66.0% of total energy consumption are from coal (NBSC, 2015). For coal resources, the mainstream idea in China is that China is rich in coal resources so there's no need to worry about the shortage of domestic coal supply. Therefore, current studies on potential constraints of China's coal production are mainly from international scholars (see Table 5). Figure 5 summaries the forecast results of China's coal from various sources. It can be seen that the difference among these forecast is still considerable. Based on these estimates, the peak year of China's coal production ranges from 2010 to 2039, and the peak production ranges from 2314 Mt to 6096 Mt. A number of reasons could be used to explain this difference, and the main reason is the URR assumptions in different studies.

China's authorities usually report very large coal resources, however, these resources have little meaning for production unless they could be found and proved that can be produced commercially.

The portion that can be produced under existing economic and political conditions, with existing technology are usually named as recoverable reserves, which is much more important than reported coal resources for modelers since it is an important part of URR. However, it is very hard to get the accurate amounts of recoverable reserves of China's coal.

The main problem is that the classification system of resources/reserves used by China before 2000 is different with those applied by international institutes. For example, the term of "coal reserves" was usually used to represent the cumulative discovered coal resources before 2000 (Wang et al., 2013a, 2013b), while in most of other systems, the "reserves" must be discovered, recoverable and remaining. After 2000, to be in line with the international systems, China released a new classification system. However, those old terms are still widely used and convey the wrong information. For example, Tu (2011) still claimed that China's total coal reserves are 1160 Gt in its report. Besides, some resource/reserve terms in China's new classification system are still hard to understand. Taking the new term of "basic reserves" as an example, it's very hard to find a corresponding term from other classification systems (Wang et al., 2013a, 2013b). According the authorities' explanations, only part of these "basic reserves" can be recovered. Besides of the difference in classification systems, another problem is that the resources/reserves data reported by different government agencies are different(Wang et al., 2013a, 2013b). Sometimes, the data reported in different reports by the same agency is also different. For example, the discovered resources in 2010 is reported to be 211.5Gt by Ministry of Land and Resources of China (MLR) in one report, however, this number is reported to be 57.51 by MLR in another report. Furthermore, many international reserves statistics and release institutes reported the wrong data. For example, China's proved coal reserves reported by World Energy Council (WEC) and BP have been 114.5 Gt for years, which has been proved to be a wrong number (Lin and Liu, 2010, Wang et al., 2013a, 2013b).

Wang et al. (2013a, 2013b) made a detailed discussion on China's coal classification system and resources/reserves data. Based on their analyses, China's coal URR are about 224 Gt. URR values shown in table 5 higher than 224 Gt are estimated based on the "basic reserves" or the average value "reserves" and "basic reserves". Therefore, in this paper, our suggested result for China's coal production is estimated to be the upper-bound value of all studies except those studies whose URR are higher than 224Gt (see Figure 7).

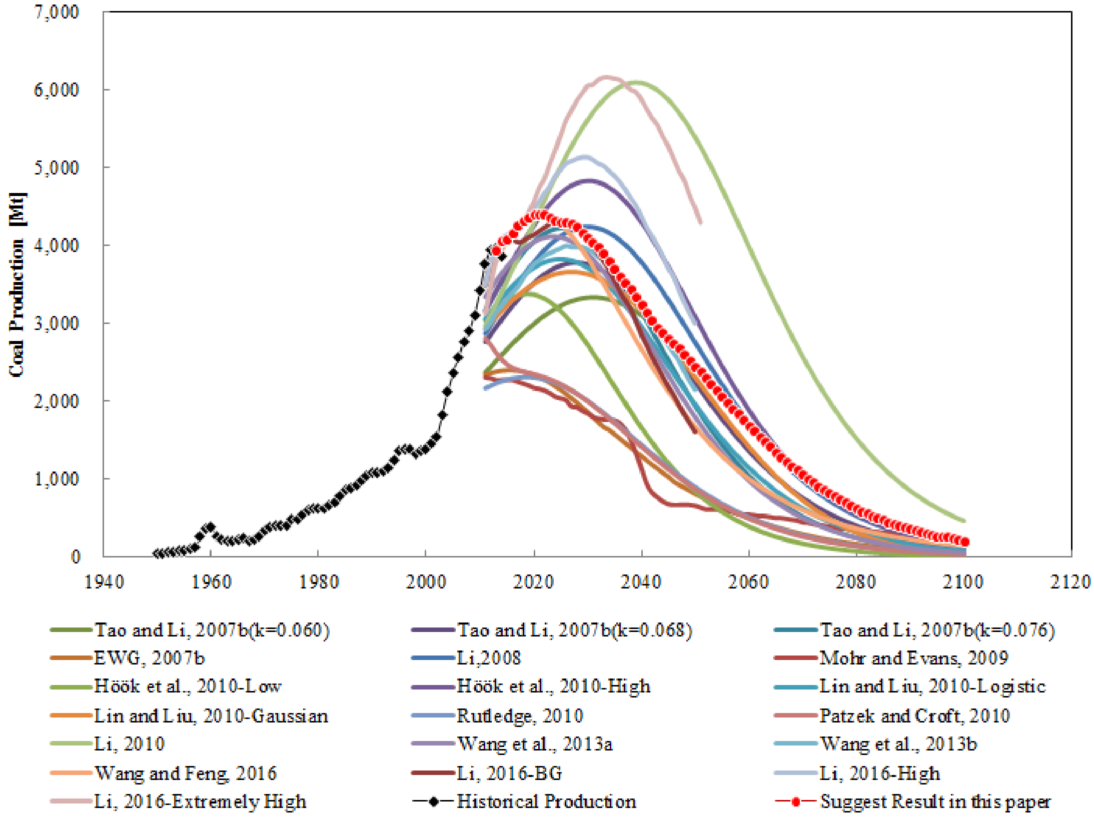

Figure 7. Production forecast for China's coal resources

Table 5. Summaries of production forecast for China's coal resources

Researchers	Methodology	URR[Gt]	Forecast results	
			Peak Prod. [Mt]	Peak Year
Tao and Li, 2007b	SD model	223	3339 3784 4228	2031 2028 2025
EWG, 2007b	Logistic model	136	2403	2015
Li, 2008	Logistic model	250	4245	2030
Mohr and Evans, 2009	SDI model	136	2340	2010
Höök et al., 2010	Logistic model	161 275	3383 4834	2019 2030
Lin and Liu, 2010	Logistic model Gaussian model	221	3830 3665	2025 2027
Rutledge, 2010	LPT model	139	2314	2019
Patzek and Croft, 2010	Multi-Hubbert model	147	2849	2010
Li, 2010	Logistic model	380	6096	2039
Wang et al., 2013a	Modified Hubbert model*	224	4119	2024

Wang et al., 2013b	Logistic model	224	3970	2027
Wang and Feng, 2016	Multi-cycle Richards model	224	4404	2021
Li, 2016	Bottom-Up Multi-Hubbert model	350 285 220	6155 5128 4310	2032 2028 2024
Summary-Literature		136~380	2314~6096	2010~2039
Comprehensive analysis*		224	4404	2021

Note:

- is not available or qualitative analysis

SDI model- Supply & Demand Interactions model

LPT model-logit and probit transforms

* is the basci case in this paper (maximum of the forecast results except those results with URR higher than 224 Gt.

A comparison of China's coal production and its coal demand is shown in Figure 8. Different with China's oil and gas, coal is the only fossil energy that China's governmental wants to control its consumption and reduce its proportion in China's primary energy consumption structure. The three demand curve showed in Figure 8 actually reflects three opinions on future China's coal demand trend. Some scholars believe that China's coal demand will keep increase until China finishes its industrialization (Shealy and Dorian, 2010; Feng, 2012) (see red line in Figure 8). Some scholars from climate institutes claimed that China's coal demand must decline immediately to reduce carbon emission and achieve China's promise that carbon emission will peak no later than 2030 (Green and Stern, 2014) (see black line in Figure 8). Most of scholars or institutes think both of above two opinions are unrealistic, they claim that coal is the only reliable resource due to its abundant resources. A realistic way to solve the environmental problem is to use coal resources with new ways (such as clean coal technologies) instead of abandon the coal resources completely. These experts thinks the coal consumption will keep increasing with a very slow growth rate or keep plateau until China finishes its industrialization (NDRC, 2009; LBNL, 2009) (similar with the green line shown in Figure 8 or maybe slightly lower).

All the above discussions on coal demand is not fully considered the potential supply constraints of China's coal resources. From Figure 8, we can see that the high demand trend in the Current Policies Scenario is hard to be met by domestic coal supply. Considering its domestic coal supply constraints, a possible pathway for future coal demand is to increase very slowly or keep plateau before 2035 and then decline steadily (lower than coal demand trend shown in green line).

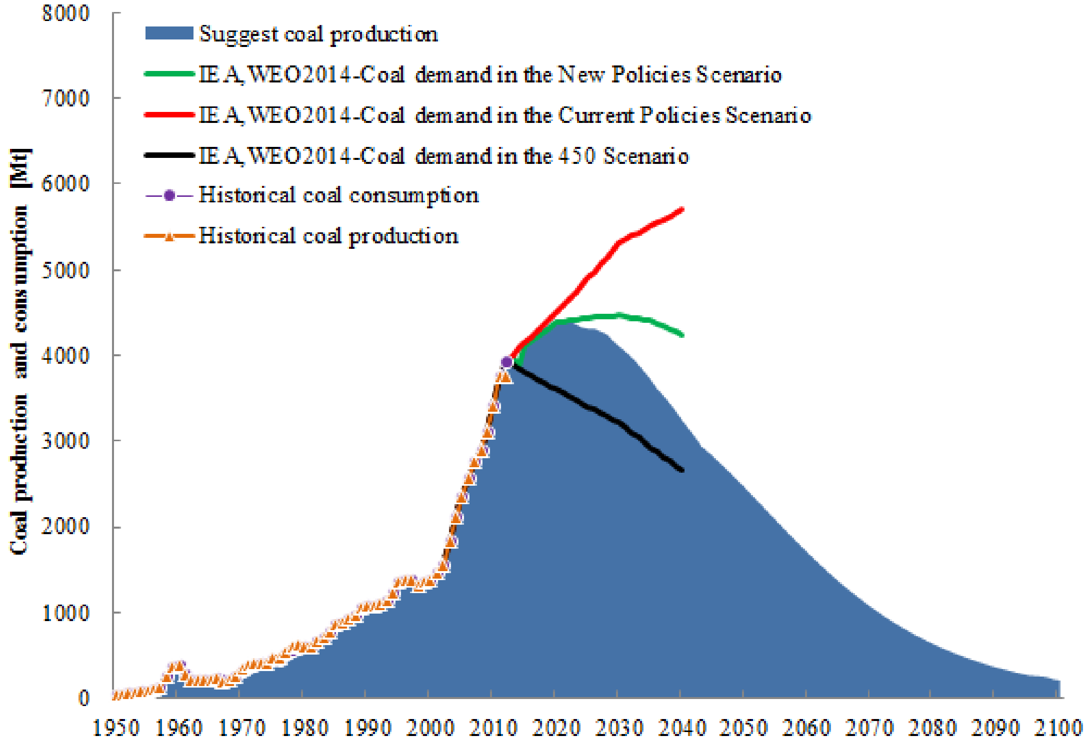

Figure 8. Comparison of China's domestic coal supply and forecast coal demand

5 EROI analysis for oil and gas

Studies shown in previous section mainly focus on the physical output of fossil energy, i.e. emphasizing final energy output without consideration of the energy input in the process of energy exploitation. However, net energy or energy surplus (i.e. energy output minus energy input) is the true value of energy resources and the real contribution to society (Lambert et al., 2014). Energy return on energy investment (EROI) is the suitable tool for net energy analysis, and it can be normally calculated on the basis of thermal equivalence by dividing energy outputs by energy inputs (Hall et al., 1981, 1986; Cleveland et al., 1984).

In this past, fossil fuel resources with high quality (which means very little energy input required to extract these resources) are abundant, and their EROI values are usually greater than 30 or 100 (Guilford et al., 2011). Therefore, we don't need to be concerned with their net energy outputs or EROIs. However, we have become aware that EROI and hence the amount of energy surplus of fossil fuels to society since the situation has been changed due to the rapid depletion of high-quality fossil fuels after 2000 (Wang et al., 2016d). Currently, there's an increasing number of studies appearing to analyze this issue (Murphy and Hall, 2010; Gupta and Hall, 2011; Hall et al., 2014). However, little of them focus on China. Current studies on EROI of China's fossil fuels are all from Hu and her colleagues (Hu et al.,2011a, 2011b, 2013, 2014a; Xu et al., 2014). The results of these studies are summarized in Figure 9.

From Figure 9, we can see that the EROIs of China fossil fuels show a decline trend mainly due to the depletion of shallow-buried coal resources and conventional oil & gas resources. The decline trend for coal's EROI is more obvious than China's oil & gas. Furthermore, Daqing oil field is the largest oil field in China and has been developed nearly 60 years. To maintain its production level, Daqing oil field has been using more advanced Enhanced Oil Recovery (EOR) methods for years, such as polymer flooding method and alkaline-surfactant-polymer (ASP) flooding method (Wang et al., 2016a). All these new methods are well known for their high cost and large environmental impact, which leads to faster decrease of Daqing oil field's EROI.

The specific values of EROI for each fossil fuels are different although they show the same decline trend. It can be seen from Figure 9 that China's coal resources have the highest EROI in the past, and its EROI value is estimated to be 29.6 in 2012 (Hu et al., 2013). The EROI of China's overall oil & gas is much lower than coal and forecast to be 9.9 in 2012 (Hu et al., 2013). Daqing oil field holds this lowest EROI value in our collected data, which is 6.4 in 2012 (Hu et a.,2014b). Wang et al. (2016e) estimated the EROI of shale gas in China for the first time, and showed that shale gas's EROI is estimated to be 33 in its median case, which is lower than U.S. shale gas but higher than China's fossil fuels, which means that shale gas could be a good choice for China to develop in future to solve its gas shortage from the perspective of net energy.

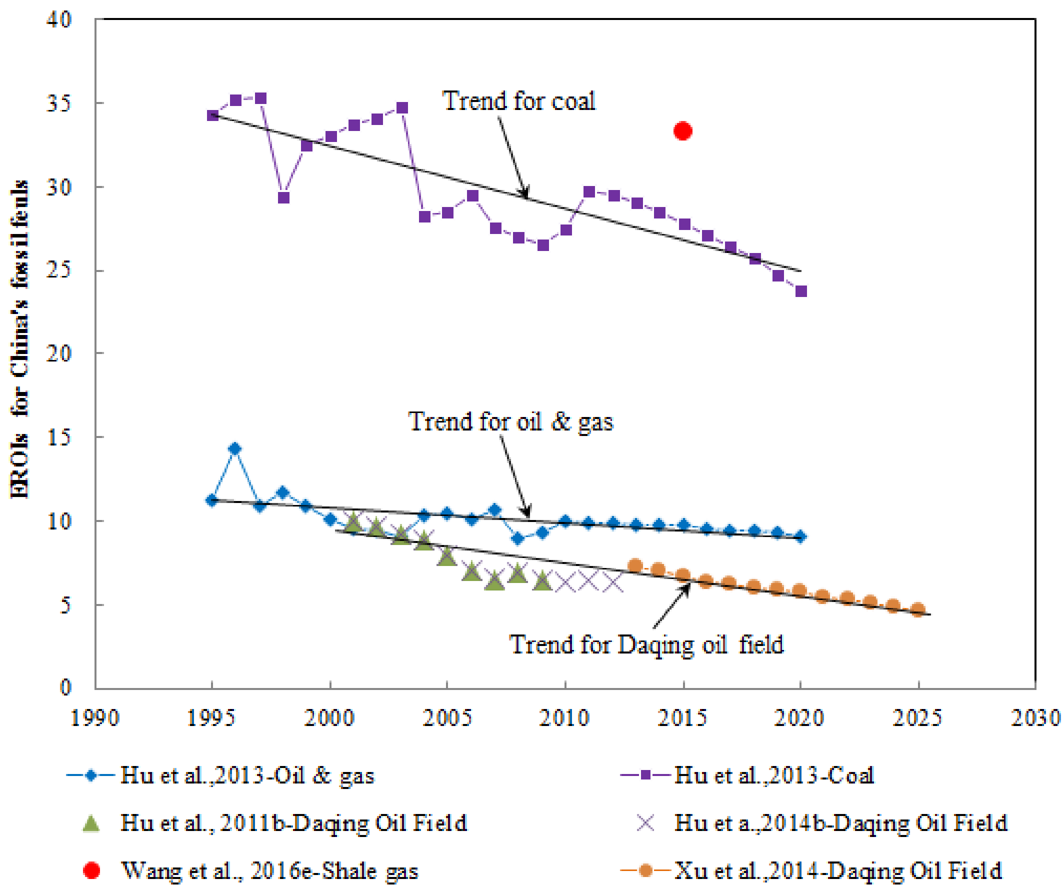

Figure 9. $EROI_{stnd}$ for different fossil fuels in China

6 Conclusions

This paper reviews the studies of China's fossil fuels from two aspects: one is the physical supply, and the other is net energy supply. Several conclusions are summarized as follows:

First, China's conventional oil production has entered its peak plateau since 2005, with a peak production of 160-170 Mt, and has declined since 2014. Current observed growth in China's total oil production is mainly from unconventional oil resources. A further analysis future unconventional oil production shows that the production growth in China's unconventional oil resources will be end in 2021, thereafter, its production will also decline. As a results, China's total oil production is forecast to peak at 2018, with a peak production of 228.4 Mt.

Second, China's conventional gas production is forecast to keep increasing and reach its peak at around 2030, with a peak production of 196 bcm. Unconventional gas resources is forecast to achieve a rapid development and its production will increase until 2058, when it reach its peak at 266 bcm. Due to this great development of unconventional gas resources, the total gas production in China will keep increasing and peak at 370 bcm in 2040.

Third, the upper-bound of China's coal production is forecast to peak at 4404 Mt in 2021, which may be supersized by most experts from China's coal industry since a mainstream opinion is that China is rich in coal and there's no need to concern for supply shortage of coal resources.

Fourth, by comparing China's fossil fuel supply and demand, we can see supply constraints of oil and gas resources will have serious impacts on China's oil and gas security. The gap between domestic production and demand of oil & gas is forecast to increase rapidly. Coal supply constraints show that high coal demand scenario is not reliable. A possible pathway for China's future coal demand is to increase very slowly or keep plateau before 2035 and then decline steadily by considering the supply constraints of coal resources.

Fifth, three key factors can be used to explain the significant difference among current studies, which are URR assumptions, applied models and the historical production data. The problem of applied models could be solved by technical methods. However, reliable URR and historical production data are usually very hard to solve due to a number of reasons, such as incomparable classification system of resources/reserves and incomplete statistical system (no statistics on unconventional oil & gas resources, and different reported data from the same government agency). To better understand the future production of China's fossil fuels, it's crucial for China to improve its data assessment and statistical system.

Sixth, studies of China's fossil fuel supply from the perspective of net energy are summarized for the first time. A steady decline trend can be observed in both coal and oil & gas industry due to the depletion of shallow-buried coal resources and conventional oil & gas resources. This decline trend is generally consistent with the approaching of peak physical production of fossil fuels. The declining of EROI means more and more energy inputs are needed to produce the same unit energy outputs. This will be unsustainable for China's society if China can't find newly abundant energy sources with high EROI value. Shale gas could be a choice for China to develop in future, but it's not enough by only relying shale gas.

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